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Investigation on partition of plastic work converted to heat during plastic deformation for reactor steels based on inverse experimental-computational method

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ABSTRACT

This paper aims at studying the ratio of plastic work converted to heat, β (Taylor and Quinney, 1934) in pressure vessel steels used in VVER-440 energetic reactors by an inverse-experimental and computational analysis. The experiments were performed with different strain rates on a thermal-mechanical testing machine from DSI (model GLEEBLE-3800). Because of the magnitude of strain rate during the experiments it cannot be modelled as an adiabatic process, also the heat transfer during the tests has to be taken into account. Analytical model was carried out to account for the conduction, convection and radiation heat losses that occur during the tests. A thermodynamically based thermo-elasto-plastic model is used to describe both the stress–strain behavior and temperature evolution in these steels under monotonic uniaxial loading. The governing equation system of thermo-elasto-plasticity was implemented in MATLAB software. It is found that β is always smaller for compression than that of tension. The results for 15Ch2MFA (bainitic structure with fine grains) show a rather strong dependence on strain rate, whereas 08Ch18N10T (austenitic structure with coarse grains) is practically independent. The results obtained by the investigation correspond to the literature.

1. Introduction

During the low cycle fatigue process the stress and strain vary in magnitude and cannot be summed. Moreover, within the low-cycle fatigue regime high cyclic stress and short fatigue lives are encountered, the plastic strain in each cycle is the predominant cause of energy dissipation. Owing the above mentioned reasons an energy based approach using plastic strain energy as a damage parameter may present an alternative to the conventional strain-based approach that has been widely used in characterizing the strain-based fatigue behavior of steels. Applying this quantity as a base fatigue parameter of the model we have to take into account the energy balance during the deformation. The dissipated heat does not contribute to the damage of the material, hence an appropriate energetic model neglects this type of energy.

According to the above mentioned reasons, the fraction of the rate of plastic work dissipated as heat β is an important quantity for carrying out a novel energetic based low cycle fatigue calculation method. This quantity can be defined as:

$$\beta = \frac{\dot{Q}_p}{\dot{W}_p}, \tag{1}$$

where $\dot{Q}$ is the thermal dissipation rate and $\dot{W}_p$ is the plastic work rate. The first modern thermomechanics based investigations on β were published by Farren and Taylor (1925) and Taylor and Quinney (1934). This quantity defines in fact the stored energy η due to the creation, rearrangement of crystal defects and formation of dislocation structures. The fraction of stored energy is defined by

$$\eta = 1 - \beta. \tag{2}$$

Over many years the Taylor–Quinney coefficient was generally assumed as a constant independent of plastic deformation and strain rate and its value was accepted as $\beta \approx 0.85$–0.95 for most metals. However to increase the sophistication of modeling, plastic deformation requires more accurate constitutive description, including better information on β. In addition, appropriate measurements on β are valuable in helping to formulate for example a

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more reliable plastic work-based fatigue model for energetic reactor component.

Determination of β can be classified into in situ and postmortem methods. In in situ methods the temperature increase is measured during the deformation or immediately after. In postmortem methods, the plastic work is introduced and the stored energy is measured later. The thermomechanical processes in in situ methods are typically adiabatic, if the deformation is fast enough to neglect the heat transfer (Mason et al., 1994; Hodowany et al., 2000; Rosakis et al., 2000; Macdoughall, 2000; Rusinek and Klepaczko, 2009). If the loading rate is much slower, the heat transfer has to be involved in the evaluation method. Zehnder et al. (1998) carried out a hybrid method which combines the measurements with finite difference simulations to calculate the heat losses that occur during the tests. This heat energy is accounted for in the final energy balance to determine the fraction of plastic work converted to heat. The majority of the investigations have been performed using infrared radiometry (Macdougall, 2000), or infrared camera (Chrysochoos et al., 1989, Rusinek and Klepaczko, 2009; Dumoulin et al., 2010) but thermocouples have also been used (Zehnder et al., 1998).

Examples for published data of determination of β for steels are given in Table 1.

This paper aims at studying the Taylor–Quinney coefficients for two structural steels applied in VVER-440 type energetic reactors. One of these materials 15Ch2MFA (21B according to A 508/508M) is a Russian developed, heat resistant CrMoV-alloyed ferritic steel and used as a base material of the reactor pressure vessel. The other 08Ch18N10T (AISI 321, 1.4541) is CrNi-alloyed austenitic steel and applied as an internal stainless cladding metal of the vessel and as a structural materials of the internal parts. We carried out this investigation in connection to our previous low cycle fatigue tests (Fekete and Trampus, 2015) to determine the plastic strain energy to failure which excludes the generated heat. Thus we performed the experiments with the strain rates in the range achieved in our earlier fatigue tests, which can not be modelled as adiabatic. The investigation was carried out based on inverse experimental-computational method to involve the heat transfer in the evaluation.

2. Experimental method and apparatus

2.1. Materials and specimen geometry

The test specimens were machined from the base metal (15Ch2MFA) and the anticorrosive cladding metal (08Ch18N10T) of the VVER-440/V-213 (Russian designed PWR) reactor pressure vessel. Nominal values of the chemical composition of the materials are given in Table 2.

The thermomechanical properties are given in Tables 3 and 4, respectively. Light microscope images of the microstructure of the alloys are given in Fig. 1. The alloy 15Ch2MFA has a bainitic structure and consists of small particles of Cr–Mo–V carbides. The other material has an austenitic microstructure with coarser grain size. The mean hardness (HV0,5) was measured to be 230 and 165 for 15Ch2MFA and 08Ch18N10T, respectively. The reader is refereed to Timofeev and Karzov (2006) for more details regarding the properties and the manufacturing process of these materials.

Quasi-static tensile tests were performed at a nominal strain rate of $5{\cdot}10^{-4}$ s^{-1} at room temperature on smooth cylindrical specimens for the test materials. The measurements were carried out on GLEEBLE 3800 testing machine. Fig. 2 shows the engineering and true stress–strain curves for both steels. The true strain is calculated by taking the logarithmic of the ratio of the initial to the current length, the true stress is obtained by dividing the load by the current cross sectional area.

The specimens used in the experiments were cylindrical specimens with gauge length of 7 mm, as shown in Fig. 3. The specimen dimensions were chosen to avoid buckling phenomena under the highest compressive forces anticipated in the test program.

2.2. Experimental details and procedures

The experiments were performed on a servo valve controlled thermal–mechanical physical simulator from DSI (model GLEEBLE-3800) starting from room temperature. This simulator has a modular design. The system consists of the load unit, connected to the "Mobile Conversion Unit" (MCU). These measurements can be realized with the Pocket Jaw. The deformation of the sample is performed by the mechanical system of the equipment. The piston is moved by an integrated hydraulic system, controlled by high-

Table 1
Previous investigations on partition of work dissipated to heat, β for steels.

Steel	Strain range [–]	Strain rate [s^{-1}]	β	$\overline{\beta}$	Reference
Carbon steel XC38	0–0.01	n.a.	0.4–0.85	0.65	Chrysochoos et al.
Stainless 304	0–0.01	0.04–0.08	0.4–0.7	0.6	Zehnder et al.
Austenitic 316L	0–0.01	0.0043	0.6–0.9	0.7	Oliferuk et al.
TRIP 800	0–0.01	0.1	0.8–1.0	0.9	Rusinek, Klepaczko
Weldox	0–0.012	0.0017	0.63–0.72	0.68	Doumulin et al.

Table 3
Thermomechanical properties of 15Ch2MFA reactor steel.

15Ch2MFA	
Thermal diffusivity	$\alpha = 1.16{\cdot}10^{-5}$ m^2/s
Thermal conductivity	$k = 40.04$ W/mK
Average emission	$\overline{\varepsilon}_R = 0.78$
Coefficient of thermal expansion	$\alpha_{CTE} = 10.9{\cdot}10^{-6}$/K
Specific heat	$C = 440$ J/kgK
Density	$\rho = 7820$ kg/m^3
Modulus of elasticity	$E = 210$ GPa
Yield Stress	$\sigma_Y = 431$ MPa

Table 4
Thermomechanical properties of 08Ch18N10T cladding material.

08Ch18N10T	
Thermal diffusivity	$\alpha = 4.1{\cdot}10^{-6}$ m^2/s
Thermal conductivity	$k = 15.4$ W/mK
Average emissivity	$\overline{\varepsilon}_R = 0.59$
Coefficient of thermal expansion	$\alpha_{CTE} = 16.6{\cdot}10^{-6}\ /K$
Specific heat	$C = 472$ J/kgK
Density	$\rho = 7959$ kg/m^3
Modulus of elasticity	$E = 201$ GPa
Yield Stress	$\sigma_Y = 215$ MPa

Table 2
Chemical composition of the test materials.

Material	C	Si	Mn	S	P	Cr	Ni	Mo	V	As	Co
15Ch2MFA	0.13–0.18	0.17–0.37	0.30–0.60	max. 0.025	max. 0.025	2.50–3.00	max. 0.040	0.60–0.80	0.25–0.35	max.0.05	max. 0.02
08Ch18N10T	≤0.08	≤0.8	≤1.5	≤0.020	≤0.035	17.0–19.0	10.0–11.0	_	_	_	_